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Under the support of ARO (Grant number: DAAH04-94-G-0086, Solid Mechanics Program, Program Director, Dr. K. Iyer), a three-year basic research program is carried out on the micromechanics of high strain-rate deformation and failure in dual-phase composites. Three composite material systems are studied: (1) tungsten heavy alloys and tungsten-based composites; (2) ceramic particle reinforced metal matrix composites; and (3) penetrator/armor material combinations. Emphasis is placed on the relationship between the microstructure and material behavior of the dual-phase solids, aiming to provide guidelines for the design of advanced armor/antiarmor systems. The outcomes of this three-year program include: (1) A better understanding of the fundamental relationship between the high strain rate behaviors and material microstructures of metal alloys and composite materials in advanced penetrator/armor systems. (2) Formulae and design charts that quantify the effects of relative volume fractions, strain and strain rate hardening, thermal softening, and the amount of damage on the overall behavior of the dual-phase solids. (3) Micromechanical models and computational schemes that can be used to predict the dynamic behavior of the penetrator and armor materials; these models and schemes may provide a basis to link the material microstructures to ballistic performance.

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THE MICROMECHANICS OF HIGH STRAIN-RATE DEFORMATION AND FAILURE IN DUAL-PHASE COMPOSITES

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1.0 Project Summary

Under the support of ARO (Grant number: DAAH04-94-G-0086, Solid Mechanics Program, Program Director, Dr. K. Iyer), a three-year basic research program is carried out on the micromechanics of high strain-rate deformation and failure in dual-phase composites. Three composite material systems are studied: (1) tungsten heavy alloys and tungsten-based composites; (2) ceramic particle reinforced metal matrix composites; and (3) penetrator/armor material combinations. Emphasis is placed on the relationship between the microstructure and material behavior of the dual-phase solids, aiming to provide guidelines for the design of advanced armor/antiarmor systems. The outcomes of this three-year program include:

- A better understanding of the fundamental relationship between the high strain rate behaviors and material microstructures of metal alloys and composite materials in advanced penetrator/armor systems.
- Formulae and design charts that quantify the effects of relative volume fractions, strain and strain rate hardening, thermal softening, and the amount of damage on the overall behavior of the dual-phase solids.
- Micromechanical models and computational schemes that can be used to predict the dynamic behavior of the penetrator and armor materials; these models and schemes provide a basis to link the material microstructures to ballistic performance.

2.0 Summary of the Most Important Results

2.1 Damage in a Tungsten Composite due to Debonding at W-W Grain-Boundaries

A theoretical study is carried out of a tungsten-based composite sustaining debonding at tungsten-tungsten grain boundaries. The tungsten composite is comprised of a continuous network of pure tungsten grains embedded in a relatively soft tungsten-nickel-iron matrix. A damage evolution model is proposed based on the Weibull statistics

relating the fraction of debonded W-W grain boundaries to the tungsten volume fraction and the applied strains. The deformation of the alloy with debonded grain boundaries perpendicular to the tensile loading direction is simulated using a three-phase finite element cell model; both constant damage and progressive damage are considered. Systematic predictions are made for the effect of debonding on the tensile flow behavior of the tungsten composite. It is shown that the stress-strain behavior of the alloy under quasistatic tensile loading is controlled by two competing trends - strain hardening and debonding softening - both evolve with the tungsten volume fraction and the applied strains.

2.2 High Strain-Rate Deformation of Particle Reinforced Metal Matrix Composites

Micromechanics analyses have been performed on the high strain-rate deformation in dual-phase composites. To gain insight, the inclusion phase is taken to be composed of spherical elastic particles, and the matrix is assumed to be elastic - perfectly plastic or power-law strain hardening; in addition, the matrix is assumed to have a power-law strain-rate hardening behavior. Systematic predictions are made of the composite flow stress as determined by inclusion volume fraction, the applied strain rate, and the strain hardening exponent and strain rate sensitivity of the matrix. It is found that the effect of strain rate is coupled with inclusion volume fraction: the strain rate hardening of the composite can be significantly higher than that of the matrix due to the constraining effect of the inclusions. A simple, user-friendly analytic formula is developed which allows one to predict accurately the rate-dependent flow behavior of the composite.

A comparison is made of the predictions of the model with the results of high strain rate experiments on a 6061-T6 Al/Al_2O_3 composite. The composite contained 20% of Al_2O_3 by volume, and was obtained from Duralcan Inc. Experimental measurements on this material were carried out using the compression Kolsky bar, the torsional Kolsky bar, and high-strain-rate pressure-shear plate impact. The experimental results showed that the composite had substantially greater rate-sensitivity than the matrix alloy. The predictions of the unit cell model are in good agreement with the experimental results, suggesting that a continuum description of the viscoplastic deformations is sufficient to model these materials.

2.3 Thermal Softening of a Tungsten-Based Composite under Adiabatic Compression

A micromechanics analysis is made of the rate-dependent thermal softening behavior of a tungsten matrix composite containing glassy particles. Under adiabatic

compression of the composite, the elastic glassy particles thermally soften at relatively high strains, enhancing the thermal softening of the tungsten-based composite, thus reducing the strain rate sensitivity. To guide the microstructural design of the particle-modified tungsten-based composite in penetration applications, predictions are made for the stress-strain behavior of the composite under overall adiabatic compression with different temperature-dependent behaviors, sizes, volume fractions of the particle and different applied strain rates. The temperature-dependent behavior of the particles is characterized by a set of exponential functions using two non-dimensional parameters and a reference temperature. The plastic behavior of tungsten is taken to be power-law strain and strain rate hardening, and power-law thermal softening. It is found that, when only the glass particles thermally soften, the strain-rate sensitivity of the composite is reduced. It is also found that when thermal softening of tungsten is included in the model, the glass particles have little effect on the thermal softening of the tungsten-based composite provided that the volume fraction of the particles is less than 15%.

2.4 A Boundary-Layer Approach for Analyzing Penetrator/Target Interactions

A new approach for modeling penetration processes in advanced armor/antiarmor systems is being developed. Attention is focused on the dynamic behavior of the material in the boundary layer at the penetrator/target interface. The goal is to establish the relationship between the thermomechanical behavior of the penetrator and target materials and the shape of the penetrator head; this relationship may enable one to understand the controlling mechanisms in penetrator/target interactions, and to predict the ballistic performance of both the penetrator and target. This work is motivated by the observation that a penetrator made of U-3/4 Ti can keep its "nose" sharp, while a tungsten heavy alloy penetrator often forms a "mushroom" head during the penetration process.

To simplify the analysis, the penetrator/target system is divided into three zones: the penetrator, the target, and the interfacial boundary layer. The material in the interfacial zone is assumed to be heterogeneous, and undergo high strain rate plastic deformation, thermal softening, and melting. Specifically, it is taken as a mixture of the penetrator and target materials; its behavior is assumed to depend only on the position along the layer thickness. At the inner and outer boundaries of the interfacial zone the material is the same as that of the penetrator and target materials respectively. The behavior of the materials in the regions outside the interfacial zone is taken to be relatively simple: no thermal softening occurs. The geometry of the head of the penetrator is described by a simple mathematical function. The target is taken to be infinitely large in the radial

direction, with an axisymmetric cavity that is consistent with the geometry of the head and the interfacial layer. A constitutive expression for the material in the interfacial zone is developed, and a number of boundary value problems have been identified. To gain insight, the deformation in a flat boundary layer is analyzed with prescribed pressure and shear stresses applied at the upper and lower surfaces. It is believed that, by taking a new approach to the penetration mechanics problem, a fundamental understanding of the penetration processes can be gained.

3.0 List of Publications

1. Lin, Z and Bao, G., "Damage in a Tungsten Composite due to Debonding at W-W Grain-Boundaries," *Acta Metallurgica et Materialia*, **43**, 1765-1774, 1995.

2. Bao, G., "On Strain-rate sensitivity of metal matrices reinforced with ceramic particles", *Proceedings of the IUTAM Symposium on Micromechanics of Plasticity and Damage of Multiphase Materials* (ed. Pineau and Zaoui, 1995), pp 11-18, Kluwer Academic, London.

3. Bao, G. and Lin, Z.,"High strain-rate deformation in particle reinforced metal matrix composites", *Acta Metall. Mater.*, **44**, 1011-1019 (1996).

4. P. R. LcDuc and G. Bao, "Thermal softening of a particle-modified tungsten-based composite under adiabatic compression", *.Int. J. Solids Structures*, **34**, 1563-1581 (1997).

5. LcDuc, P. R. and Bao, G., "Thermal softening of glassy particle modified tungsten", in *Proc. ASME Aerospace Division and Materials Division* (ed. R. C. Wetherhold et al, 1996), AD-Vol. 51/MD-Vol. 73, ASME, pp. 497 - 505.

6. Bao, G., Rapacki, E. Jr., and Bilyk, S., "A boundary-layer approach for analyzing penetrator/target interactions," *Proceedings of 14th Army Symposium on Solid Mechanics* (eds. K. Iyer and S. C. Chou), in press (1997).

7. Chichili, D. R., and Ramesh, K. T., "Dynamic Failure Mechanisms in a 6061-T6 Al/Al_2O_3 Metal-Matrix Composite," *International Journal of Solids & Structures*, **32**, 2609-2626, 1995.

8. Yadav, S., Chichili, D. R., and Ramesh, K. T., "The Mechanical Properties of a 6061-T6 Al/Al_2O_3 Metal-Matrix Composite at High Rates of Deformation," *Acta Metallurgica et Materialia*, **43**, 4453-4464, 1995.

4.0 List of All Participating Scientific Personnel

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P. R. LeDuc, Graduate Research Assistant.